

## Photoinjector Working Group Summary

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## Outline of discussion topics

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- Expected laser performance in power, stability (amplitude and phase).
- What can be done and what may become available in laser pulse shaping?
- What are the open problems to realizing SRF guns of high-current?
- What performance can we expect from the gun?
- Reliability of accelerator design codes.
- ERL merger issues

## A list of the talks

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- **Triveni Rao: The photocathode scenario and laser requirements**
- **Hiromitsu Tomizawa: Laser pulse shaping experiments**
- **Yuelin Li: Schemes of arbitrary laser pulse shaping**
- **James Rosenzweig: Ultra short initial laser pulse drives to ellipsoid electron bunch at the end**
  
- **Mike Cole: The  $\frac{1}{2}$  cell superconducting gun design and status**
- **Ram Calaga: HOM, multipactoring and coupling in the  $\frac{1}{2}$  cell gun**
- **Jacek Sekutowicz: What field performance can we expect from the gun.**
  
- **Sergey Kurennoy: The reliability and accuracy of PARMELA for RF guns**
- **Xiangyun Chang: Performance of the electron cooler gun**
- **Jorg Kewisch: Optimization of gun parameters**
- **Dimitre Dimitrov: Initial 3D Electromagnetic RF Gun Simulations with VORPAL**
- **James Rosenzweig: One of the possible scenario of a halo formation.**

# Laser charges

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- **What are the laser issues for the photocathode?**
  - Assuming CsK2Sb type cathode
  - Assuming diamond amplified cathode
- **What laser development work is needed?**
- **What are the current capabilities of laser pulse shaping?**
- **What are the prospects of arbitrary transverse - longitudinal laser pulse shaping?**
- **What are the necessary developments in laser shaping?**
- **What instrumentation will be needed?**
- **What needs to be done on instrumentation?**
- **Develop an R&D plan.**

# Photocathode Research

## CsK<sub>2</sub>Sb cathode

QE	Current	Current density	Charge	Uniformity	Lifetime
>10%	50 mA	0.8 mA/mm <sup>2</sup>	5 nC	?	Days
9% @ 352 nm/ ~10% <b>@532 nm</b>	2/ <b>32</b> mA <b>@ 25% DF</b>	1 mA/mm <sup>2</sup>	60 nC	System limited	Weeks/days/ Hours

## Cathode with Diamond Amplifier

Gain	Max current	Current density	Bunch length	Energy spread
100	50 mA	1 mA/mm <sup>2</sup>	30 ps	<0.4 ev
>50	0.6 mA	8 mA/mm <sup>2</sup>	?	?

## Cathode Research Directions

**Bialkali Cathode:** QE, Life time, Operation at High Current, Low Temperature, Contamination

**Diamond Amplifier:** Response time, Energy spread, Operation at High Current, Low temperature, Capsule

**Interface:** To Gun, To Diamond amplifier

## Laser Research

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Commercial Lasers can meet power and stability requirements

Frequency regime needs research

Fiber laser may be a viable option for future

Several beam shaping techniques are available

### Laser Research Directions

- Establish tolerances
- Establish Minimum Emittance Needed and corresponding laser profile
- Research on Beam Shaping techniques

# 3D- Laser Beam Shaping system

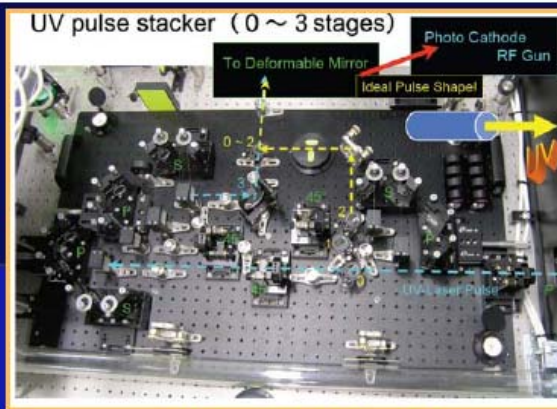
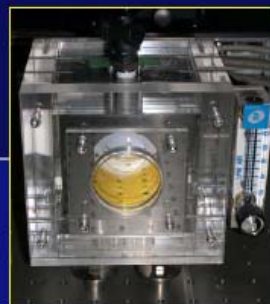
**UV- Laser source (total stability!)**

Laser Pulse Energy : **1.4% @THG**

24 hrs; 1 month long

Pointing Stability & Reproducible

Timing Jitter < 1 ps



## Temporal Profile:

Pulse duration: 2.5 ~ 20 ps

**UV- Pulse Stacker**

Pulse duration: 2.5 ps

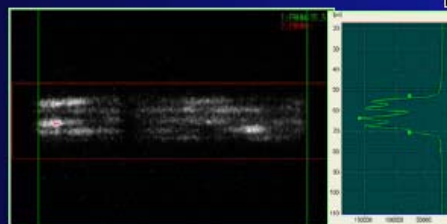
Pulse duration: 10 ps

Diameter: 1 mm

10 pps

**Pulse Stacker**

**Deformable Mirror**



Streak Image of stacked pulses

## Spatial Profile:



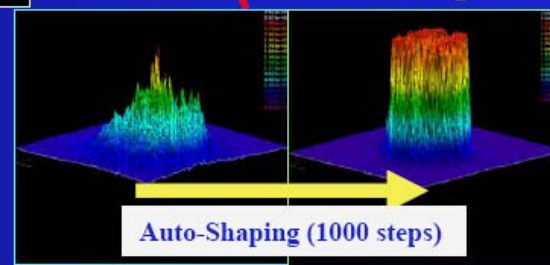
Gaussian

Distribution: Flattop

**Deformable Mirror**



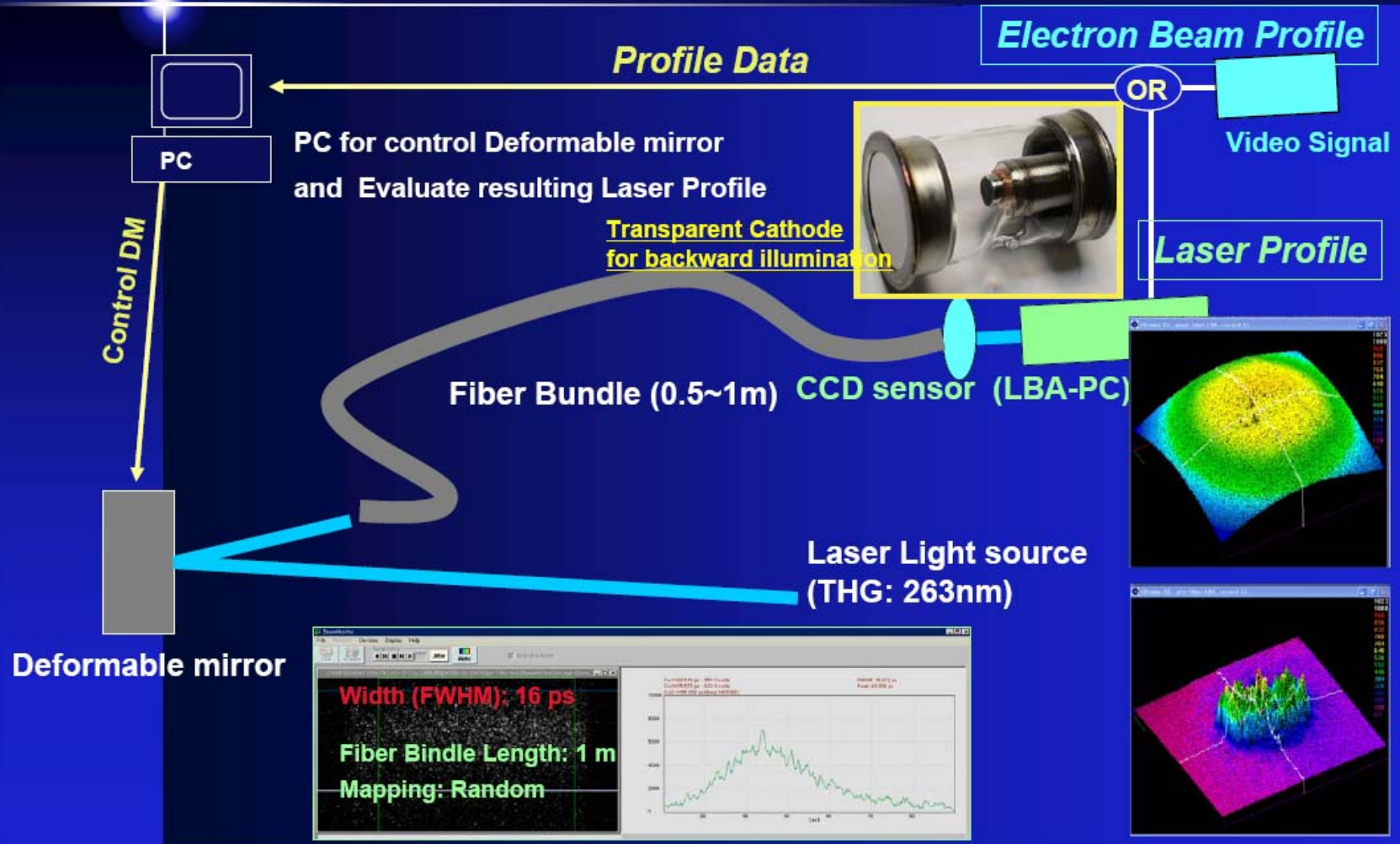
**Flattop**



Auto-Shaping (1000 steps)

# Closed Control System for Fiber Bundle with computer-aided Deformable mirror

Fiber Bundle is ideal as a 3D-shaper! (directly monitoring electron bunch shape!)

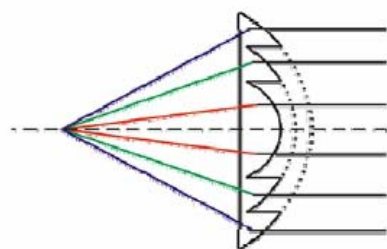


...and a ... ..

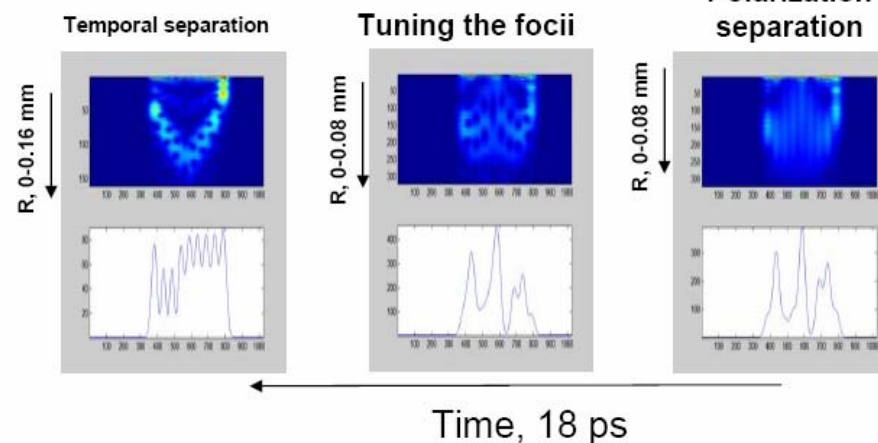
## 3-D pulse shaping using zoned lens

- Divide a lens into concentric zones and take control of
  - Timing by lens thickness
  - Slice spatial shape by zone geometry
  - Intensity by profiled transmission and polarization
- Such lens ideally can transform a laser pulse into any 3-D shape
  - Needs excessive design and engineering effort

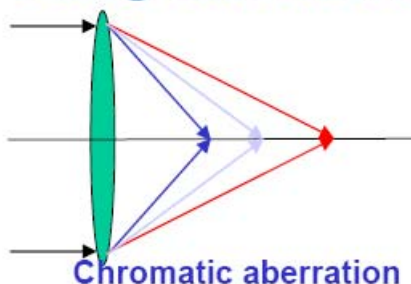
A zoned lens



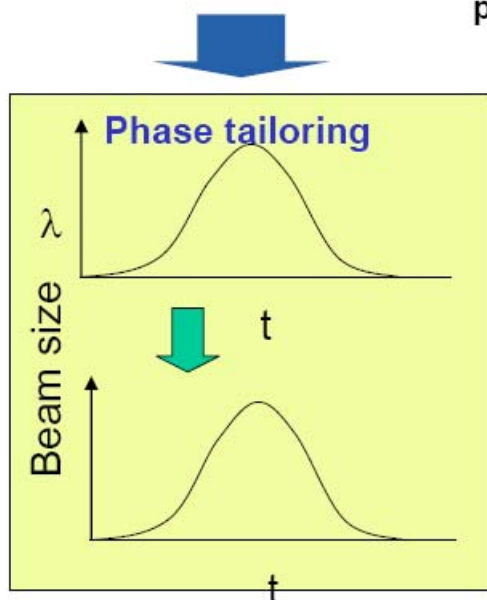
Pulse generated with different parameters



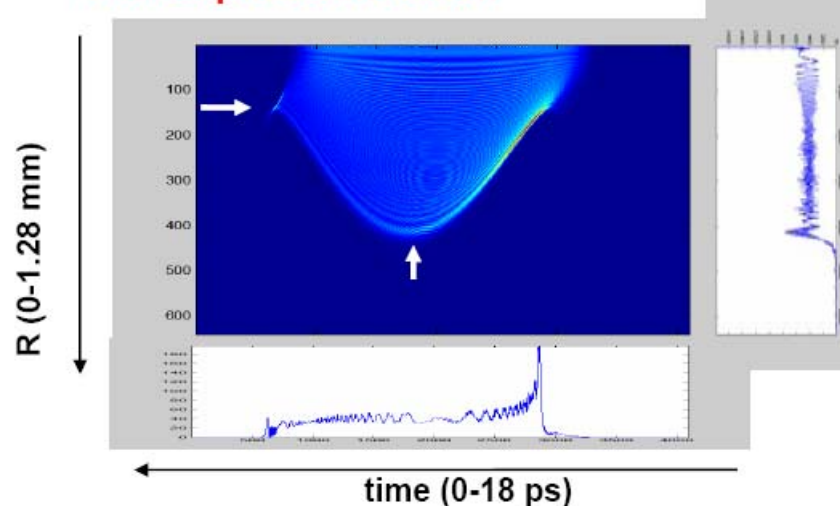
## Ellipsoidal pulse generation Using chromatic aberration with laser phase tailoring



- A regular lens always has a chromatic effect
- With modern technology the phase can be tailored to make use of the chromatic effect
- Quasi ellipsoidal pulse is generated
- Need pre-shaped beam and large big bandwidth to reach the parameter for e-cooler

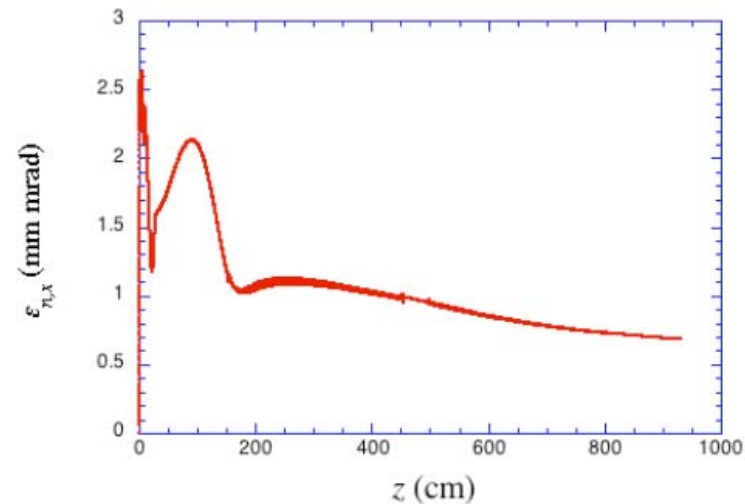
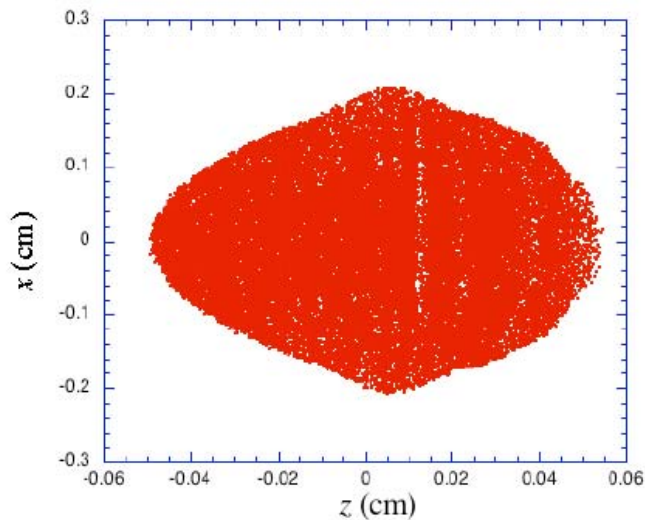


### Wave optics simulation



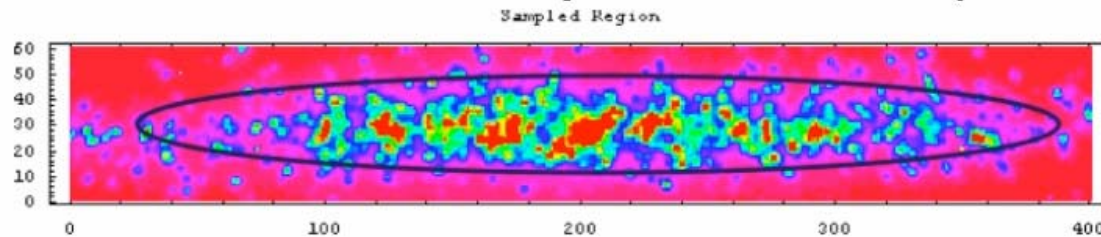
# Dynamic beam shaping using longitudinal space charge

- Very short pulse laser (in our case 5 psec FWHM is OK), expands to uniformly filled ellipsoid - “perfect” beam
- Consistent with emittance compensation
- Excellent longitudinal phase space
- Simulations done; experiment underway

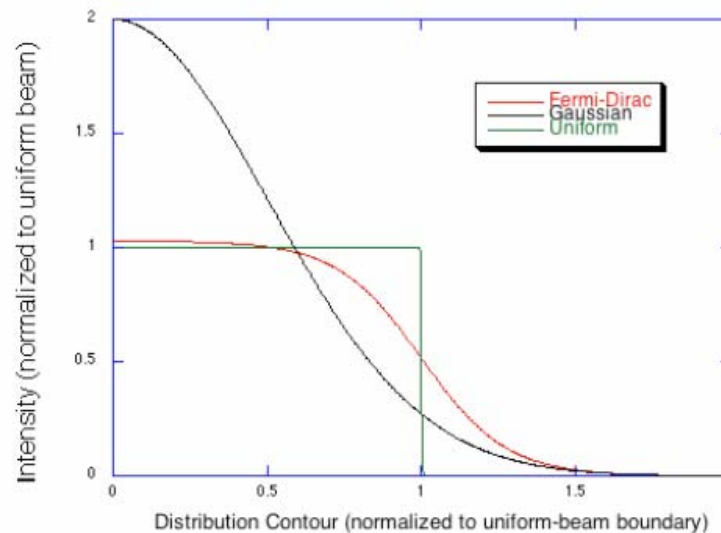
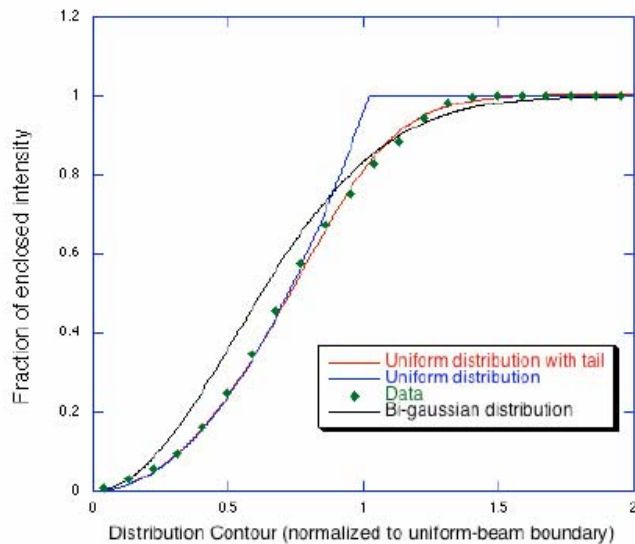


PARMELA simulations for SPARC experiment

# UCLA/SPARC Experiments (Frascati)



- Aerogel-based streak camera measurement
  - $x$ - $t$  distribution
  - Pulse lengthening follows PARMELA predictions
- Likelihood analysis using signal enclosed inside ellipse
- Signature of uniform beam with tail observed



# Laser issues

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- Photon budget and QE
  - 10% QE acceptable, with 70% transport/QE loss
  - Lifetime needs to be understood, compensated (consistent w/10% assumption?)
  - Bi-alkali is plan A (conservative)
  - Diamond/secondary emission is plan B
- Research plan is detailed for success <2 years for ERL operations
- Answer should be ready for decision on cooling, with +overhead in time
- Commercial 5W uv system available (bi-alkali case OK) 355 nm 3rd harmonic (YAG)
- Pulse length 5 psec in uv FWHM
- Fiber lasers can add photon budget overhead? Not yet commercially available, but labs are working hard (LLNL)
- Cost <800\$k

# Laser issues

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- Transverse pulse shaping methods
  - Measure electron distribution, not just laser
  - Must be consistent with longitudinally smooth laser
  - Interested in uniform and ellipsoidal projection distributions
- Evaluate insertion losses
  - Deformable mirror <20% in UV
- Laser stability and pulse shape time evolution must be consistent
- Dynamic beam optimization based on ultra-short beam, relying on space-charge was discussed
  - 1<sup>st</sup> experiments at Frascati (UCLA)

# Laser issues

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- Longitudinal pulse shaping methods
    - More simulation to specify advantages in pulse shaping
      - Include temporal delay, temperatures, non-uniformity
      - Develop tolerance budget
      - Evaluate alternate schemes (ellipsoids...)
    - Are they consistent with photon budgets?
  - For beer can, solutions go before amplification:
    - DAZZLER integrates into intelligent system
      - Need to evaluate suitability for application
    - Undercompression
  - Pulse-stacker post-amplification (20% insertion loss)
    - Ellipsoid solutions in uv (wait for higher QE)
    - Fiber bundle (high risk, 20% insertion loss)
    - Laser beam quality and handling
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## Laser: conclusions

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- Laser time structure is very relaxed compared to ultra-high brightness photoinjectors
  - Many manipulations are easier
- Average current demands are difficult
  - Photon budget is difficult w/o diamond cathodes
  - Fiber lasers should be examined more thoroughly
- Methods for transverse shaping/uniformity **MUST** be included in laser development
- Longitudinal shaping has difficulties; must examine risks and benefits

## SRF Gun charges

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- **What is the performance expected of the SRF gun and at what level of confidence?**
- **Develop an R&D plan**

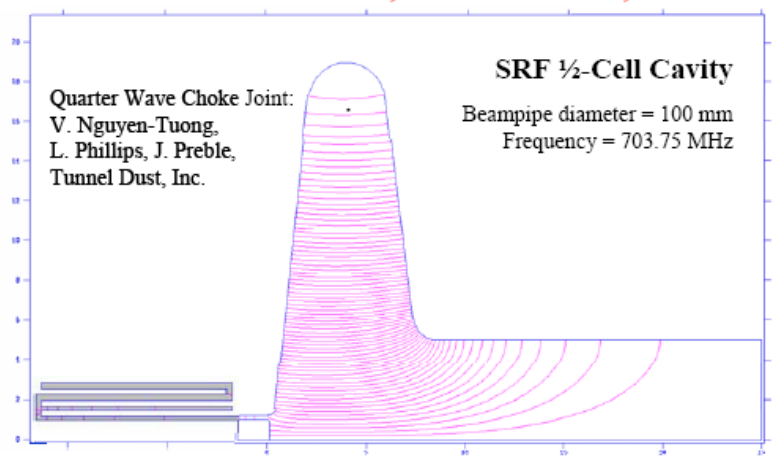


# SRF Injector Design



Advanced Energy Systems, Inc.

0.5 Cell, 703.75 MHz, 0.5 A



## Objectives & Comments

- Design & fabricate a 0.5-cell Superconducting RF gun & choke joint fed by two 0.5 MW RF power couplers
- Test device on the BNL ERL
- Collaboration with JLAB, BNL, FZR & other FEL stakeholders

## Target Parameters

Frequency	703.75 MHz
Energy	2 MeV
Current	500 mA with PRF of 352 MHz
Bunch Charge	1.33 nC
Transverse Emittance*	5.5 mm-mrad rms normalized
Longitudinal Emittance*	42 keV-psec rms
Energy Spread*	3.1 %
Bunch Length*	7.2 psec rms

\* No emittance compensation

## Schedule

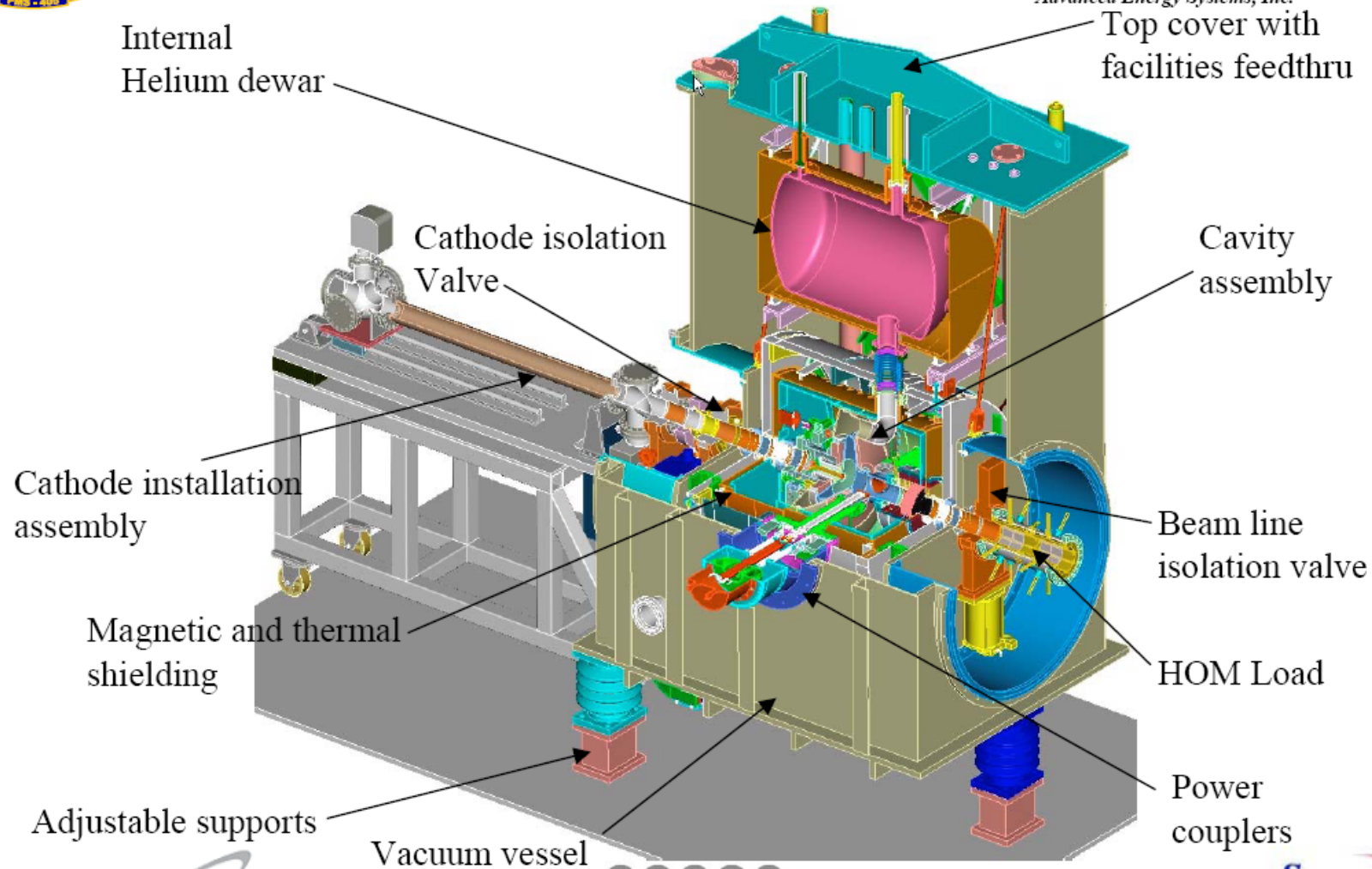
- Choke configuration downselected – 6/04
- Preliminary design review – 1/05
- Niobium ordered – 12/04
- Testing alternate choke joint – completed 3/05
- Final design review 12/05
- Delivery to BNL by ~ 3/08
- Initial testing completed at BNL by ~ 12/08



# Cryomodule Configuration



Advanced Energy Systems, Inc.



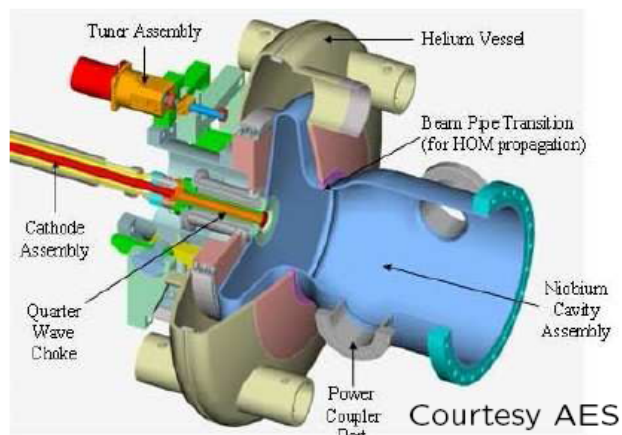
**BROOKHAVEN**  
NATIONAL LABORATORY



# SRF 1/2 - CELL GUN & ISSUES

## Rama Calaga

### $\frac{1}{2}$ Cell SRF Gun

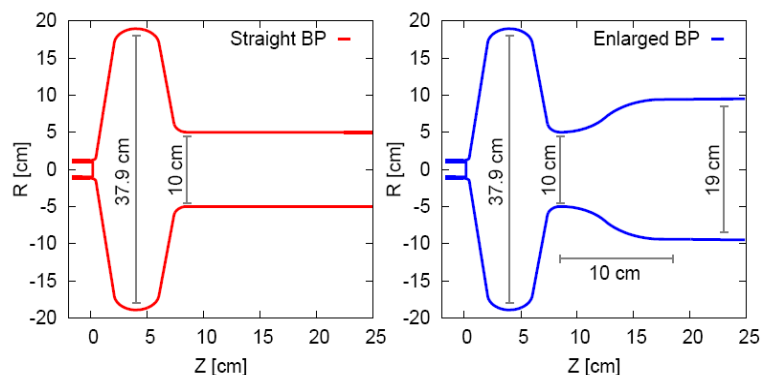


- Generation of ampere class CW beam
- $\beta < 1$  and varying
- Low  $\epsilon_{x/y}$  &  $\delta E/E$
- $E_z$  at the cathode
- Strong Coupling  $Q_{ext} \sim 10^4$
- Coupler Kicks
- Multipacting
- HOMs & Stability Criteria
- Cathode Issues and Isolation

Cavity Design	Right Cell
Frequency	703.75 MHz
Iris Radius, $R_{iris}$	5.0 cm
Wall Angle, $\alpha$	$6.5^\circ$
Equatorial Ellipse, $R = \frac{B}{A}$	1.1
Iris Ellipse, $r = \frac{b}{a}$	1.2
Cav. wall to iris plane,	1.0 cm
Active cavity Length, L	8.5 cm
Center to equator end	18.95 cm
Avg. Beta, $\langle \beta = \frac{v}{c} \rangle$	0.587

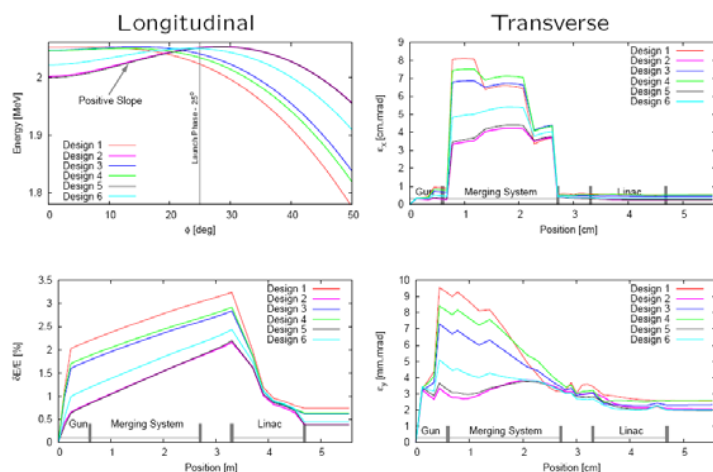
# SRF 1/2 - CELL GUN & ISSUES

## Beam Pipe Transition



- HOM Damping ☺
- FPC Coupling (field level  $< 10^2 \rightarrow 10$  cm away) ☺
- Mechanical Design (manufacturing, valves etc..) ☺

## Energy Spread & Emittance



- Optimize Iris Radius
  - $f_{HOMs}$  &  $f_{cut-off}$
  - Trapped Modes
- Beam pipe transition
  - HOM damping
  - FPC Coupling
- Optimize  $L_1$  &  $L_2$ 
  - Energy Vs. Phase Slope
  - Longitudinal Emittance
  - Transverse Emittance
- Optimize cavity ellipses
  - Peak fields, R/Q, etc...

# What field performance can we expect from the gun ?

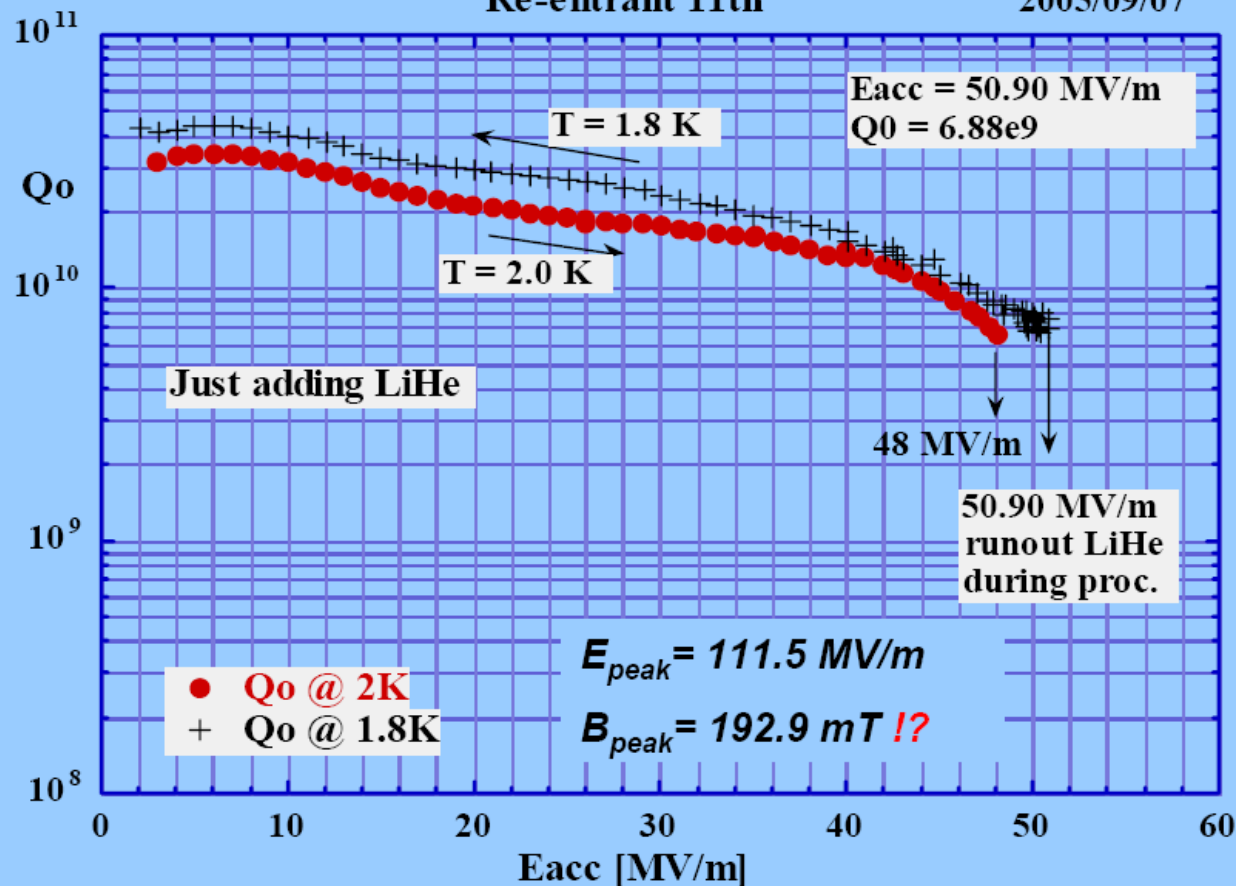
## 1. Nb limit and cavity shape

Single cell performance show that we are able to reach critical magnetic flux of niobium ( $\sim 190\text{mT}$ ). The corresponding peak electric fields on the cavity wall, depending on the shape of a cavity, can be as high as  $112\text{ MV/m}$ .

Re-entrant 11th

2005/09/07

Courtesy K. Saito



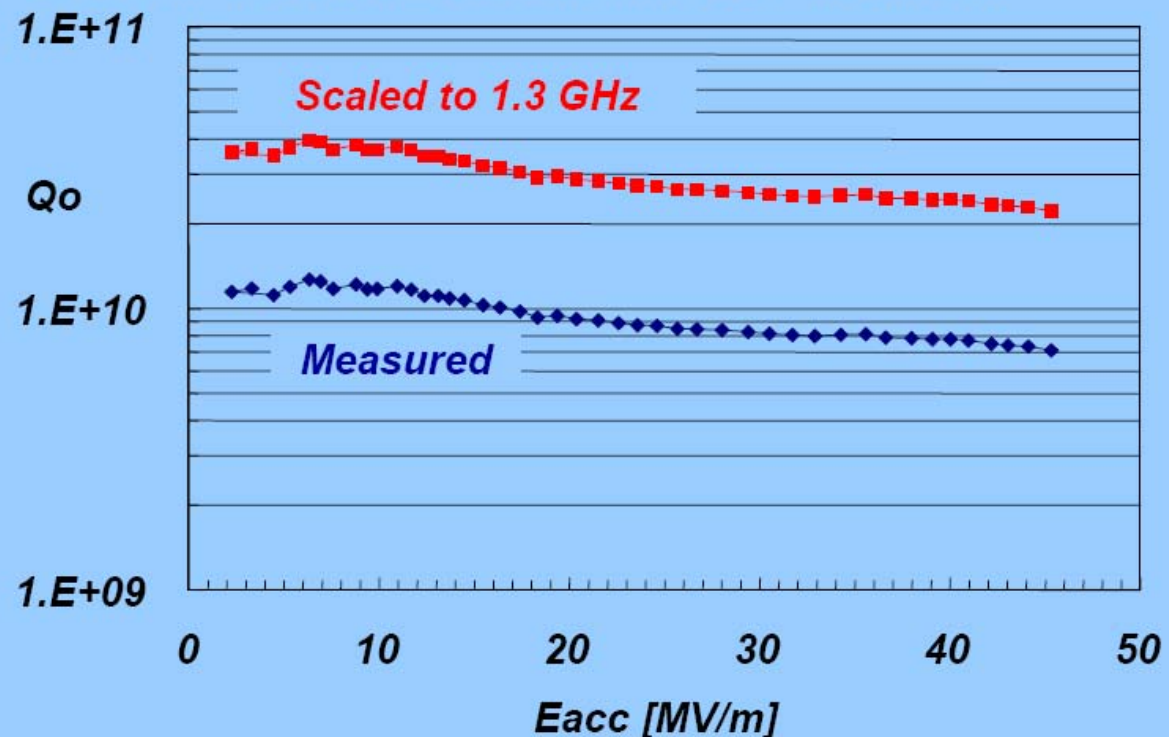
# What field performance can we expect from the gun ?

## 1. Nb limit and cavity shape, cont

We still should work on intrinsic quality factor, to ensure low cryogenic losses and field emission free operation of the guns ( small or no dark current).

LL 2.3 GHz

It seems to me that big grain ( or single crystal) material is right way to go. Surface smoothness of the order of 30 nm is reachable even with BCP treatment.



Courtesy P. Kneisel, JLab

$Q_0 \sim 2 \cdot 10^{10}$  for 1.3 GHz at  $E_{peak} = 85.5$  MV/m if  $R_s$  dominated by BCS



## SRF gun design issues

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- **E=60 MV/m peak field and  $Q=10^{10}$  in SRF cavities demonstrated**
    - 100 MV/m peak observed
    - < 30 MV/m field
  - **RF Photocathode gun design issues**
    - Overall, Nb gun maintains field gradients
    - Compensation solenoid magnetic field at the SRF Gun surface is important
    - Cesium (multi-alkali) cathodes in SRF gun still must be demonstrated
    - Choke joint demonstrated @ 150% (grooves)
    - Nb cryogenic tests to be completed
  - **RF coupler**
    - Probable limit on power in gun
    - Quadrupole fields from coupler and effects on the beam need to be evaluated
    - Mitigation methods: quadrupole symmetrization, coaxial coupler
  - **HOM analysis**
    - No problems anticipated, evaluation should be completed
    - Coaxial coupler may introduce problems
    - Ferrite-based solutions
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## Beam Dynamics Charges

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- What improvements can be expected in the beam brightness?
- What is the current simulated best performance for emittance vs. charge?
- What are the uncertainties in the simulation of emittance of the electron beam?
- How good is the comparison between simulation and experimental measurements?
- What experimental measurements should be done?
- What improvements are needed in the simulation codes?
- What instrumentation will be needed?
- What needs to be done on instrumentation?
- What do we know about halo generation?
- What needs to be done in the halo area?
- Develop an R&D plan.

# PARMELA Validation

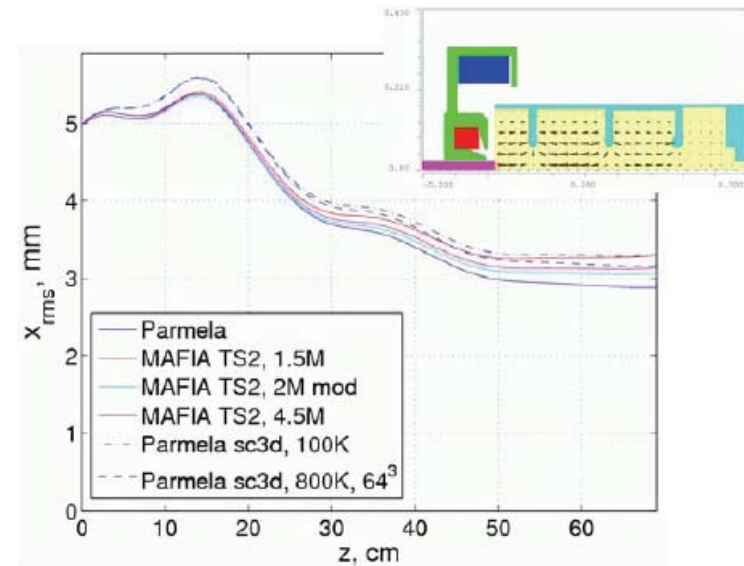
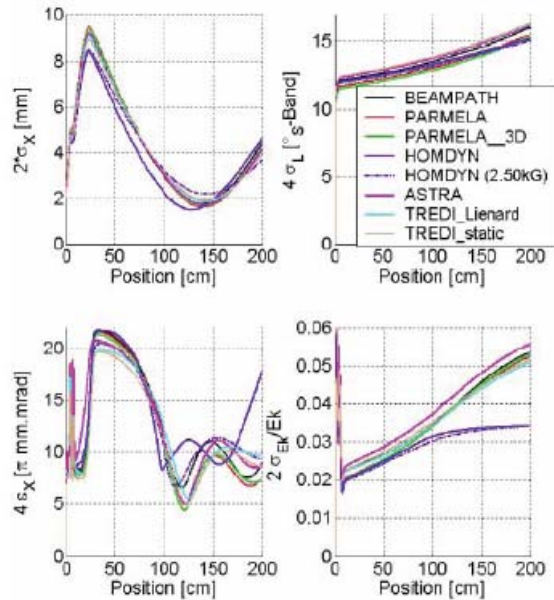
Examples: LANL – AFEL, APEX. Boeing high-current injector. More recent:

Fermilab A0 Photoinjector  
UCLA Neptune Facility  
DUVFEL

SLAC Gun Test Facility (GTF)  
LCLS design effort (<140 MeV)  
Industrial & medical linacs

**Almost every modern electron linac built  
has been designed with PARMELA.**

## Codes



Many comparisons: in general, good agreement between different codes. **Parmela is often used to benchmark other codes.**

# PARMELA : Summary

- Good tool for both normal and super conducting photoinjectors.
- Likely **most widely tested code of this kind**. Extensive comparison with measurements; often a benchmark for other codes.
- For **photoinjector (PI) design** the current **Parmela (v3.40)** is **accurate and reliable** provided that:
  - PI layout is close to axisymmetric one (cavity fields, laser spot, etc);
  - PI has a moderate field gradient ( $\sim 10\text{-}30$  MV/m) on the cathode;
  - Pulse length is not very long.
- Modifications (e.g., “energy bins”) can remove some of these limitations.
- In general, Parmela “**does a pretty good job if one puts in the correct information about the accelerator**” (*L. Young*). Unfortunately, “**Parmela does not do very much checking on what is physically consistent in the input.**” Some work is still left for the designers...
- Other codes: **ASTRA** (DESY), **IMPACT-T** (LBNL): 3-D+(...), etc.

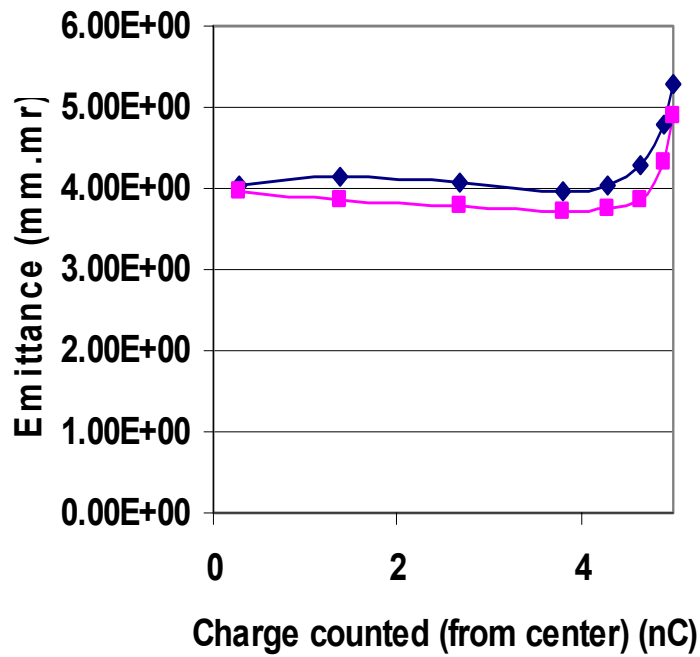
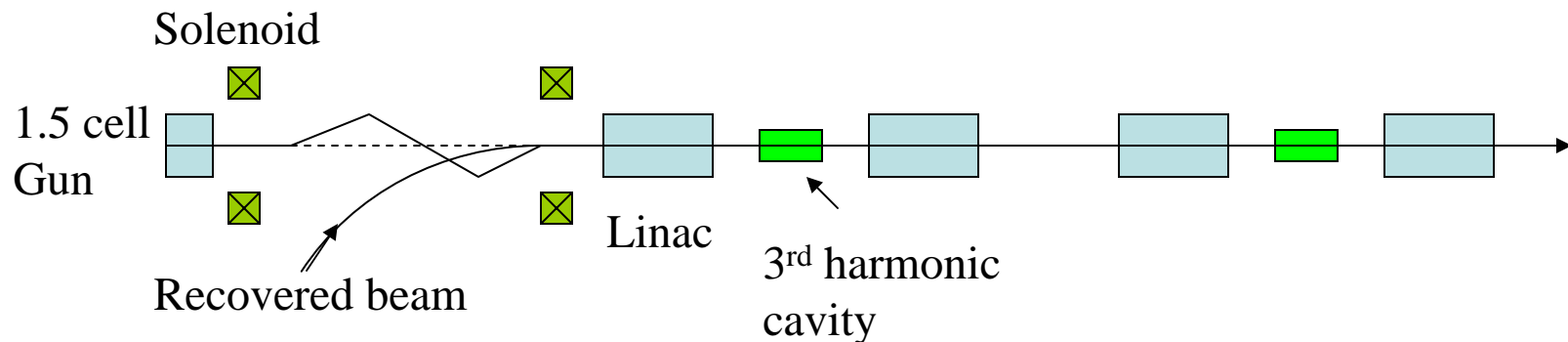
The beam quality at linac exit is sufficient for RHIC electron cooling (from simulation)

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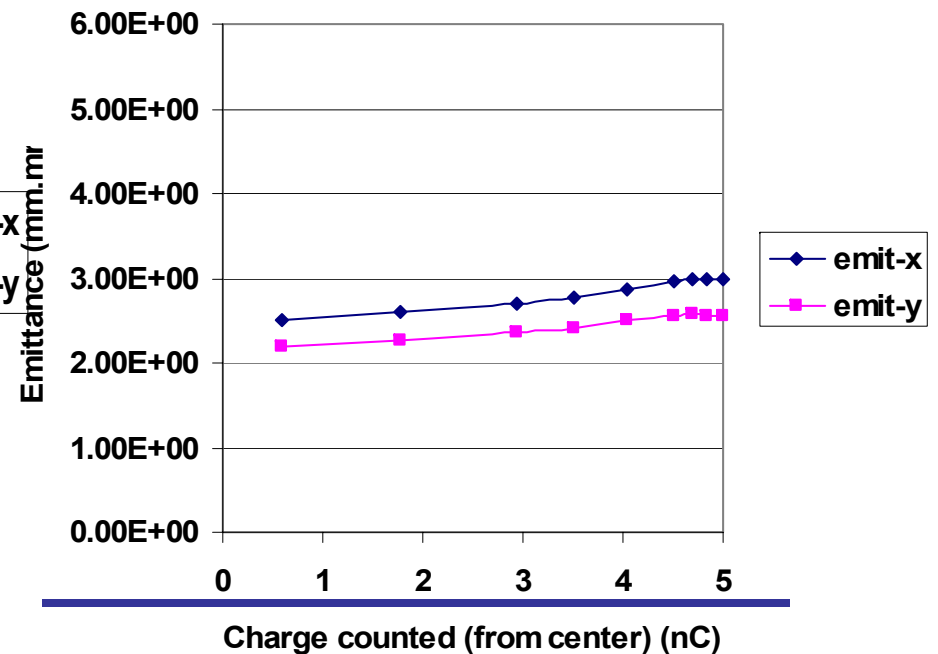
Charge / bunch = 5nC			
Laser distribution	$\epsilon_{x(\text{final})}$ (mm.mr)	$\epsilon_{y(\text{final})}$ (mm.mr)	Energy spread
Elliptical	2.5	2.0	$0.18 \times 10^{-3}$
Beer can	3.0	2.5	$0.25 \times 10^{-3}$
Gaussian	5.3	4.9	$0.29 \times 10^{-3}$

$R_{\text{max}}$ (mm)	$\pm\phi_{\text{max}}$ (deg)	$\phi_i$ (deg)
5.6	10	35
5.5	11.6	40
5.0	10	35

- The beam quality is actually better than what is indicated by the emittance parameter. The “core” emittance is much better for the case of Gaussian distribution laser. The cooling force simulation should be done using the “real” distribution from the electron beam simulation.



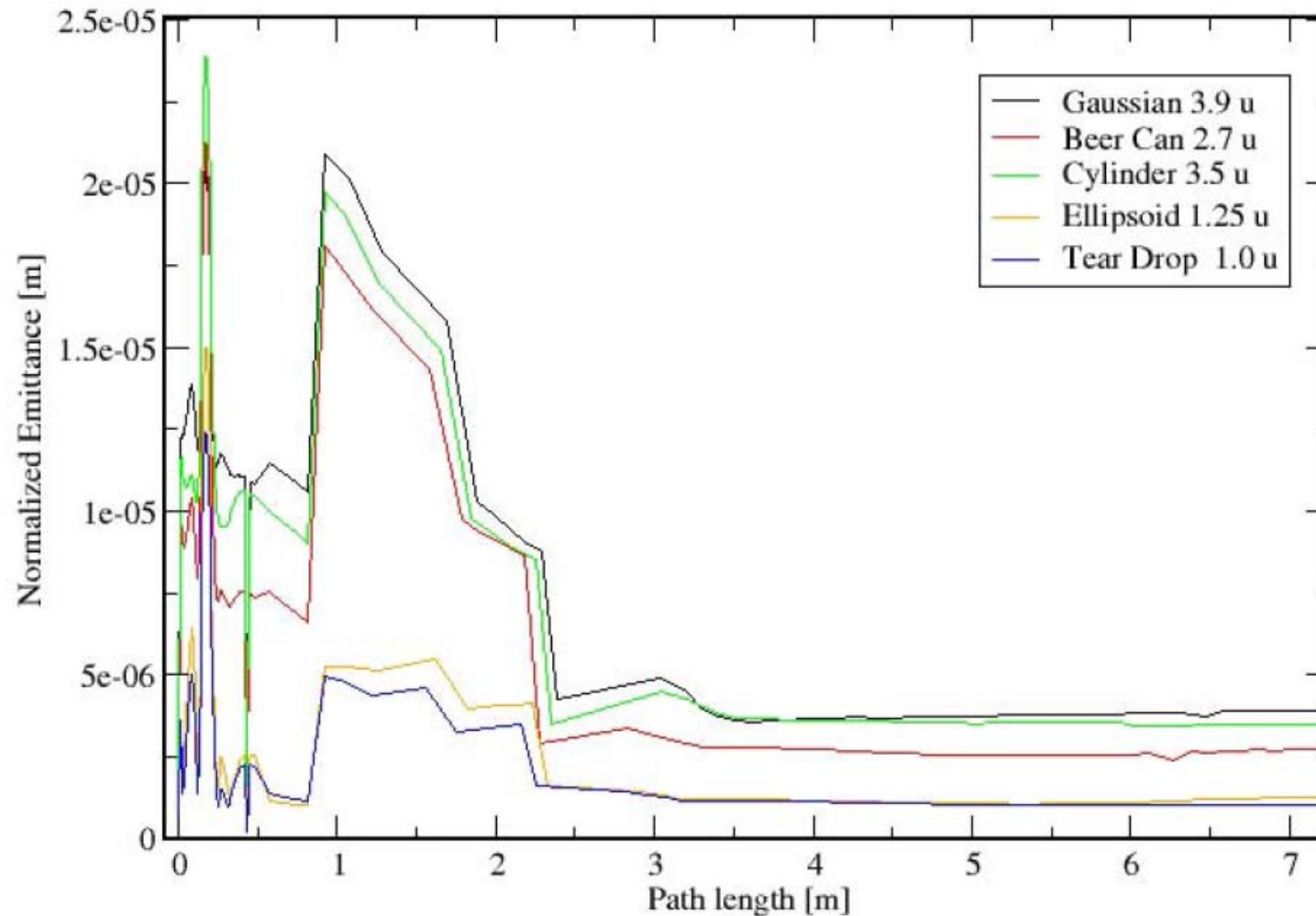
**Gaussian**



**Beer can**

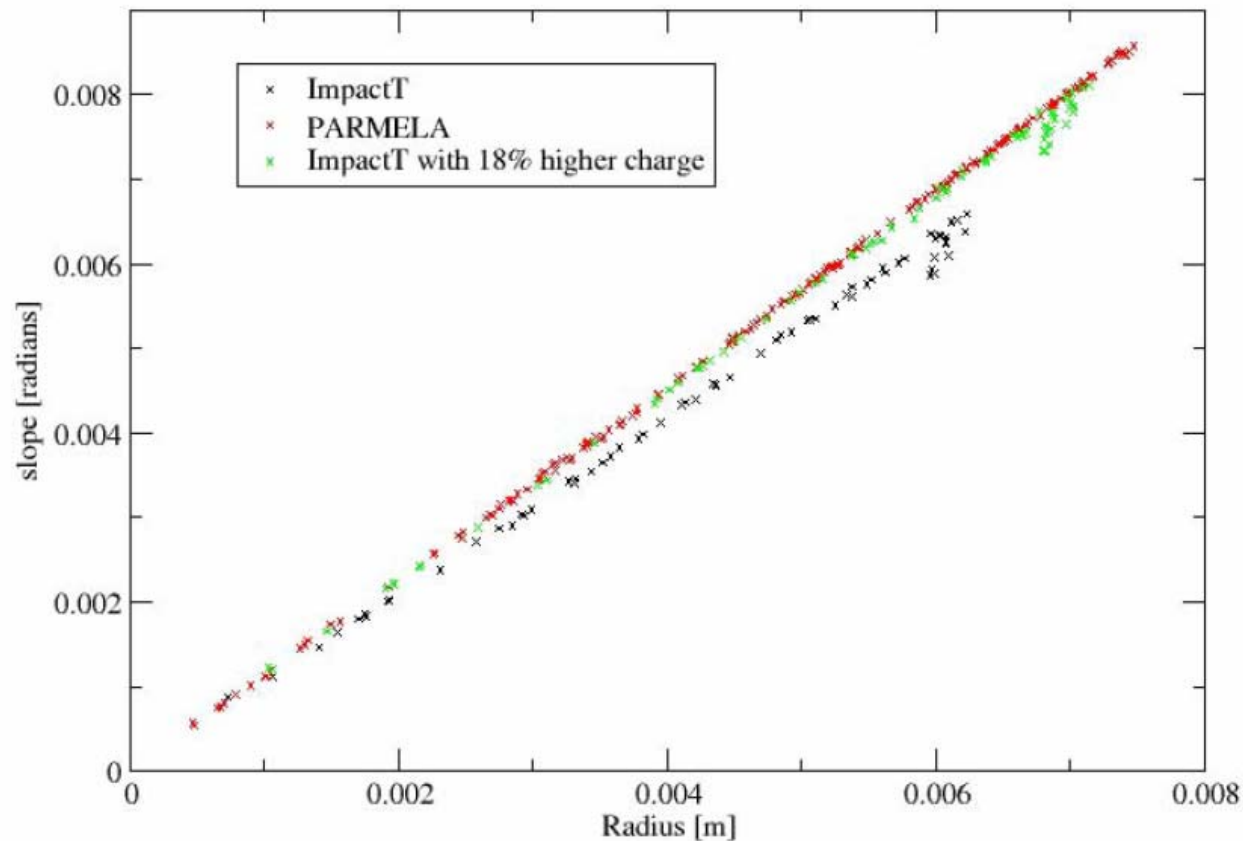
Workshop, May 24-26, 2006

# Optimized Beam Emittance for various Bunch shapes



# Comparison PARMELA -ImpactT

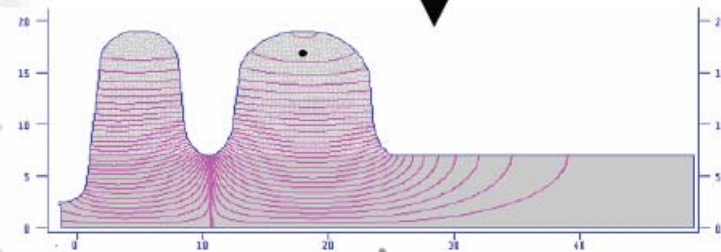
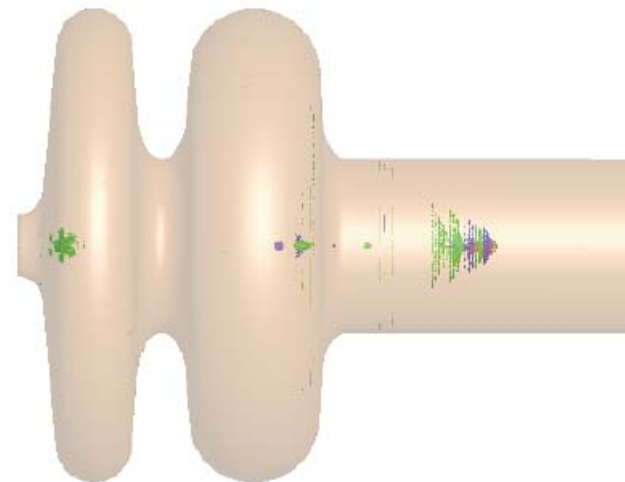
Transverse Phase Space - Middle Slice





## VORPAL, 3D massively parallel PIC code, is uniquely suited for high accuracy modeling of 3-D Accelerating Cavities

- Initial simulations were done with parameters for the 1.5 cell RF gun under development in BNL.
- The results were benchmarked with PARMELA.
- The 3D geometry of the gun is included in VORPAL:
- Based on a SUPERFISH axial symmetry description:

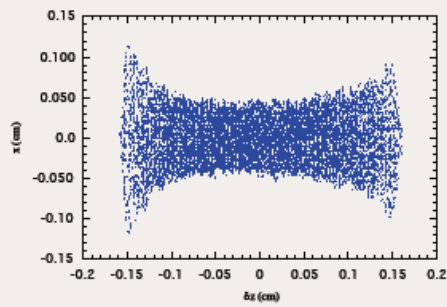




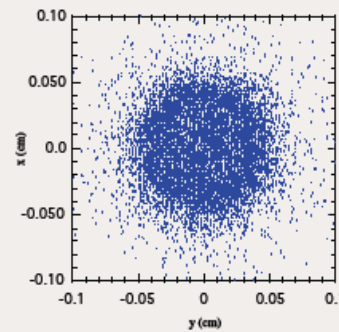
## 3D PIC simulations with VORPAL demonstrated capabilities for simulations of SRF electron guns in complex 3D geometries

- Initial simulations and preliminary benchmarking of VORPAL results show reasonable agreement with PARMELA.
- VORPAL has the unique functionality to study the effects of wake fields on propagating multiple bunches in RF guns cavities.
- Future studies will focus on using higher accuracy algorithms, perfectly matched layer boundary conditions, multiple bunches, secondary electron emission from diamond amplifiers, and photocathode physics.

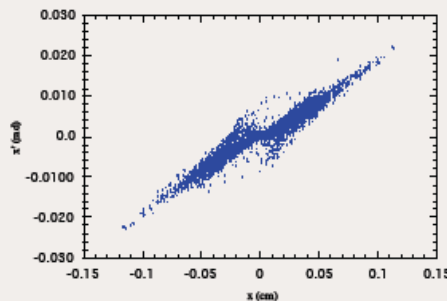
# Multiparticle simulation picture: LCLS case (beer-can, uniform)



Spatial (x-z) distribution



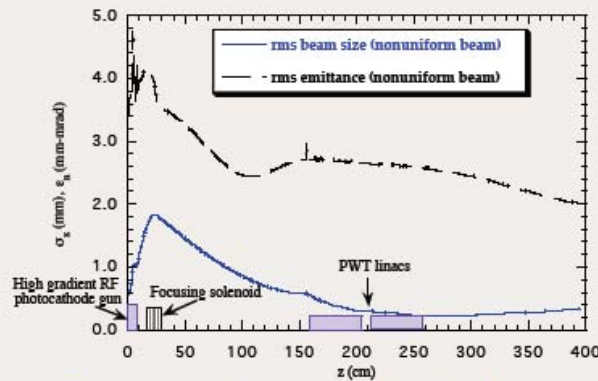
Spatial (x-y) distribution



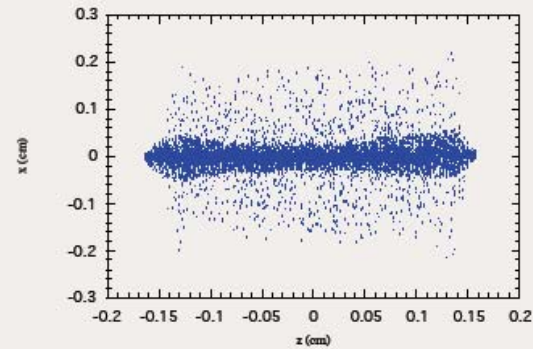
Trace-space distribution

- Case I: initially uniform beam (in  $r, t$ )
- Spatial uniformity reproduced after compensation
- High quality phase space
- Most emittance is in beam longitudinal tails (end effect)

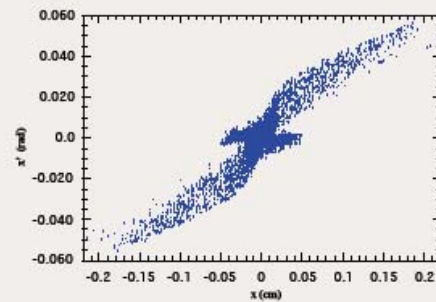
# Multiparticle simulation picture: Nonuniform beam



Larger emittance obtained



Spatial ( $x$ - $z$ ) distribution



Trace-space distribution

- Case II: Init. Gaussian beam
- Most emittance growth due to nonlinearity
- Large halo formation

## Beam Dynamics issues

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- PARMELA does good job (excepting bends)
  - Experimental benchmarking of PARMELA is often very good, depends on problem
  - LLNL PARMELA support is in doubt
- Understand beam dynamics in bends (beyond PARMELA)
- Examine existing and developing codes (push IMPACT-T?)
  - Benchmarking PARMELA and IMPACT-T (with CSR)
- Develop and use PIC approach, e.g. VORPAL
  - 3D problems especially
- Quadrupole fields from couplers effect on beam dynamics must be evaluated

## Beam dynamics (cont.)

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- Near cathode dynamics *in codes* need to be understood
- Examine space-charge contribution to bunch lengthening, shaping
  - Potential Preconstruction Z-bend experiment on existing system (Zeuthen, FNAL, LANL)
  - Scaling with physical parameters of beam, Z-bend
  - Benchmark codes
- 5 nC gives 2.5x3.0 large advantages
- mm-mrad w/beer can, ellipsoid gives 2x2.5
- Uncertainties driven by unknown imperfections, poor understanding of bends
- Impact of thermal emittance on design “envelope” should be examined
- Simulation of errors
  - Tolerance budget development
- Halo generation is possible, need to examine entire accelerator/transport

## Conclusion

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- Thanks to the working group for stimulated all discussion